

# **Atmospheric Optical Propagation**

Stephen Hammel  
SPAWARSYSCEN San Diego code 5548  
49170 Propagation Path  
San Diego, CA 92152

Phone: (619) 553-4578 fax: (619) 553-1417 email: [stephen.hammel@navy.mil](mailto:stephen.hammel@navy.mil)

Dimitri Tsintikidis  
phone: (619) 553-1418 fax: (619) 553-1417 email: [dimitris.tsintikidis@navy.mil](mailto:dimitris.tsintikidis@navy.mil)

Alexander M. J. van Eijk  
TNO Defence, Security and Safety, P O Box 96864, 2509 JG The Hague, Netherlands

Award Number: N0001408WX20215

## **LONG-TERM GOALS**

The Atmospheric Optical Propagation project is developing a suite of accurate models for optical propagation in the marine atmospheric boundary layer. Our objective is to provide an atmospheric effects characterization package for existing and emerging Navy applications.

## **OBJECTIVES**

- 1) The Advanced Navy Aerosol Model (ANAM) family of aerosol extinction models represents the development of an accurate determination of optical extinction in the coastal marine environment. A series of upgrades to ANAM has refined and improved the performance of ANAM. This goal for this task is to complete the ANAM development and provide the ANAM as a stand-alone tool for other propagation assessment models.
- 2) A flexible and comprehensive suite of software tools has been a long-term project that we call EOSTAR (=Electro-Optical Signal Transmission And Ranging). EOSTAR is designed to assess the effects of the atmosphere on propagating optical (either visible or IR) beams. EOSTAR has been developed to provide the results of applied research to 6.4 applications, such as tactical decision aids. The EOSTAR project is an end-to-end model development for infrared and visible absorption, scattering, refraction, and scintillation using local meteorological input data.
- 3) In many of the important surface Navy applications, optical turbulence can be just as important for beam degradation as extinction (and often more important). This project seeks to define better methods to obtain input data for the models, as well as an improvement in model performance. The technical objective is an improvement of the prediction and use of the refractive index structure parameter  $C_n^2$  and the proper use of this quantity to accurately model all turbulence-related beam degradation within the littoral marine atmosphere.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2008</b>		2. REPORT TYPE <b>Annual</b>		3. DATES COVERED <b>00-00-2008 to 00-00-2008</b>	
4. TITLE AND SUBTITLE <b>Atmospheric Optical Propagation</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>SPAWARSSYSCEN San Diego code 5548,49170 Propagation Path,San Diego,CA,92152</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>Code 1 only</b>					
14. ABSTRACT <b>The Atmospheric Optical Propagation project is developing a suite of accurate models for optical propagation in the marine atmospheric boundary layer. Our objective is to provide an atmospheric effects characterization package for existing and emerging Navy applications.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES  <b>7</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

## APPROACH

1. The central organizing emphasis for the optical propagation task is the creation of a model suite which will accurately predict propagation in the marine near-surface atmosphere from source to sensor, or from source to target. Our work focuses on the two primary atmospheric sources of signal or beam degradation: extinction by gases and aerosols, and optical turbulence. Both of these phenomena are complex and difficult to model, and a successful description requires an interplay between field experiments and analysis.
2. **Dr. Lex van Eijk** (TNO Defence, Security and Safety, Netherlands) directs the ANAM analysis and upgrade. Dr. van Eijk's critique and re-design of the ANAM model has required a review of all of the weakest elements of the model, and each of the 4 component modes of the ANAM 4 model is currently under review. Mode amplitudes, mode diameters, and the shape and definition of the basic component modes in ANAM are being changed to better reflect the underlying physics (instead of computational convenience).
3. EOSTAR is a flexible simulation tool to assess the performance of optical & infrared systems in the near-surface marine atmosphere. All of the first-order beam degradation factors such as extinction, turbulence, and mirages are calculated, and the results are available as a synthetic camera image. This complete array of modules enables the simulation of a propagation path in any sort of environmental condition.
4. **Dr. Dimitri Tsintikidis** (SSC San Diego) directs the development of EOSTAR capabilities. A particular emphasis is the problem of periscope detection against maritime backgrounds. The propagation features in EOSTAR are well-developed and tested; the emphasis in our current program is the development of models for potential targets for an imaging system, and the development of background simulation and assessment.
5. We have also initiated the development of wake signature models for several periscope speeds. Due to interest in wavebands in the visible and near-IR, it is important to carefully model reflectance as well as emissivity features of the sea surface. It is also critical to make these multi-spectral calculations of reflectance and emissivity for foam and bubbles in the near-wake.
6. **Dr. Steve Hammel** leads the effort to develop turbulence assessment methods that are organic to the optical instrument, and to innovate single-ended assessment methods. In addition, this task includes the testing of optical turbulence models and selection of the most useful analytical approach to predict the effects of turbulence on laser beam degradation.

## WORK COMPLETED

**ANAM Upgrade:** The ANAM development focused on two tasks: the humidity dependence and the introduction of a surf zone mode. In the humidity task, an analysis was made of an aerosol dataset acquired at Ballast Point and the Naval Amphibious Base at the entrance of San Diego Bay. It was concluded that humidity was indeed an important (though not necessary dominant) factor in the modeling of the observed aerosol concentrations. A local aerosol model was developed. Future work will build on this analysis and include modifications in the ANAM humidity equations with the aim to

better represent the aerosol measured at that location. Any new algorithm will be validated with an independent aerosol data that includes a wide range of humidity values.

The surf mode development was co-sponsored by a project supported by the Joint Technology Office. On the basis of two experiments (at Scripps CA and at Duck NC), a surf aerosol source function was developed. The shape of the surf production mode is taken to be equal to that of sea spray aerosol. The amplitude is driven by wave energy dissipation, which is available to the Navy for locations worldwide through the DIOPS model. ANAM provides a simple estimator of wave energy dissipation on the basis of wave height. While this estimator neglects effects due to bottom topography and surf zone width, it offers an engineering approach in case DIOPS is not available.

The surf mode in ANAM also contains a transport factor that accounts for the decrease in the concentration of aerosols generated over the surf zone with distance to the surf zone due to deposition. The transport factor is implemented as a multiplier (between 0 and 1) for the initial amplitude of the surf zone. The factor is calculated as function of fetch (distance to shore against the current wind direction) and instantaneous wind speed. The equations used are a parameterization derived from the 1D-transport model MACMod by Gilles Tedeschi of the University of Toulon. The dependence on particle size in these equations has for the moment been neglected and a center radius of 2.5  $\mu\text{m}$  has been used.

**Optical Turbulence Assessment:** A primary interest is to enable the measurement of critical optical turbulence parameters utilizing methods that are flexible and can be used in various scenarios, including shipboard at-sea measurements. One solution is a development of a single-ended optical sensor to measure the optical turbulence parameters  $C_n^2$  and  $r_0$ , since these quantities characterize the turbulence intensity along horizontal, slant, or vertical paths.

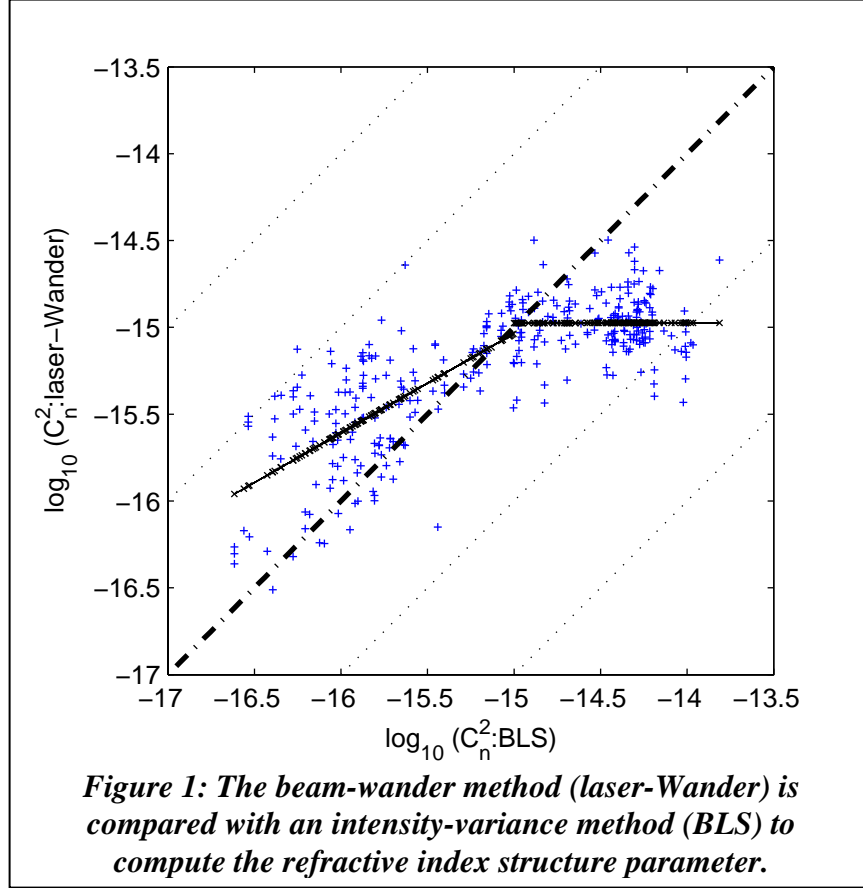
During the Navy Zuniga Shoal Propagation Test, an intensive operational period in November-December 2006 included a laser link sharing the same propagation path as all other optical measurements. The laser test, conducted by personnel from the Naval Air Warfare Center in China Lake CA, produced high fidelity intensity imagery of the propagated YAG 1.064  $\mu\text{m}$  laser beam. The NAWCWD (China Lake) laser optics group provided us with both raw imagery and data analysis to enable a comparison with a scintillometer analysis. A collimated laser beam at 1.064  $\mu\text{m}$  was propagated on the same path as the scintillometer experiment, and intensity data from the collimated beam was collected at a 56 cm aperture receiver.

We developed algorithms to deduce  $C_n^2$  directly from the measured laser beam wander, and in Fig. 1 these datasets were compared with measurements from the commercial scintillometer, the Scintec BLS2000.

The beam-wander method utilizes an analysis by Churnside and Lataitis to determine the refractive index structure parameter  $C_n^2$ :

$$\sigma_{col}^2 = 0.97 C_n^2 D^{-1/3} L^3$$

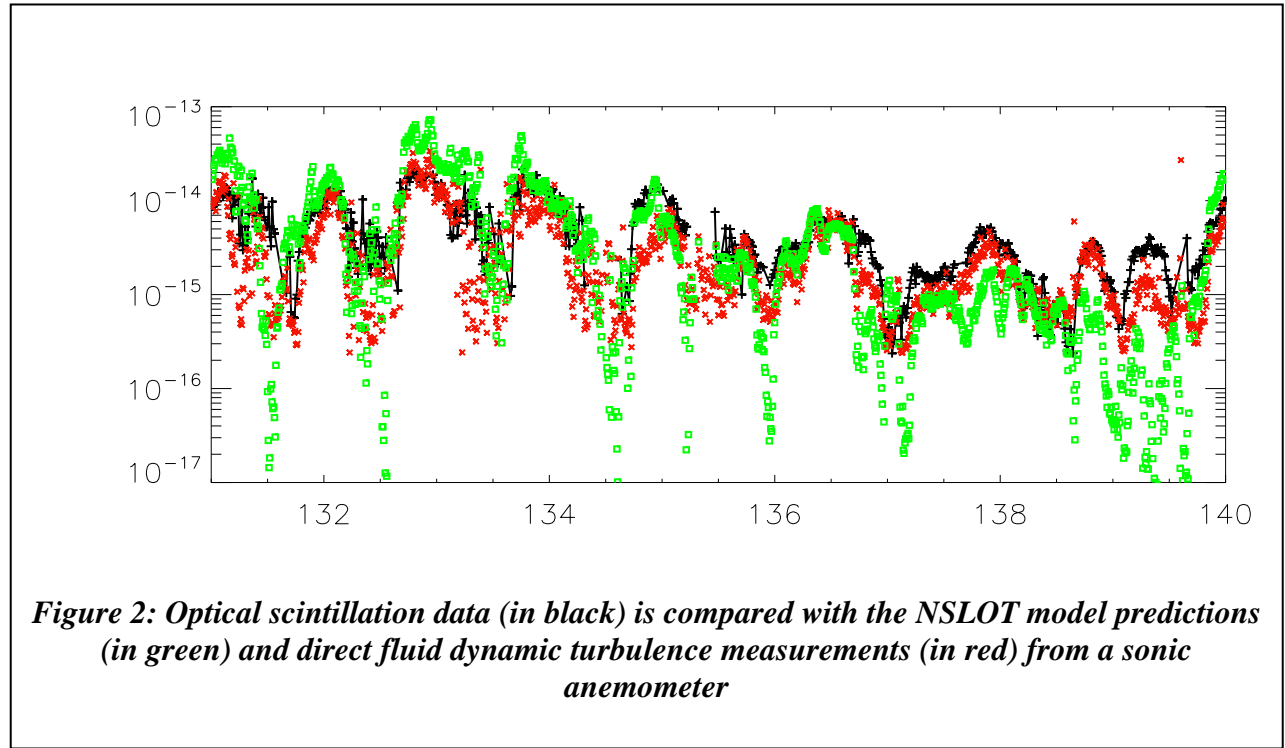
where the variance  $\sigma_{col}^2$  is determined from the change in focal plane position of the centroid of the laser intensity map. This centroid is found for each of the 300 frames in the data sequence, and from the variance, the equation above can be solved to determine the  $C_n^2$ : laser-wander value.



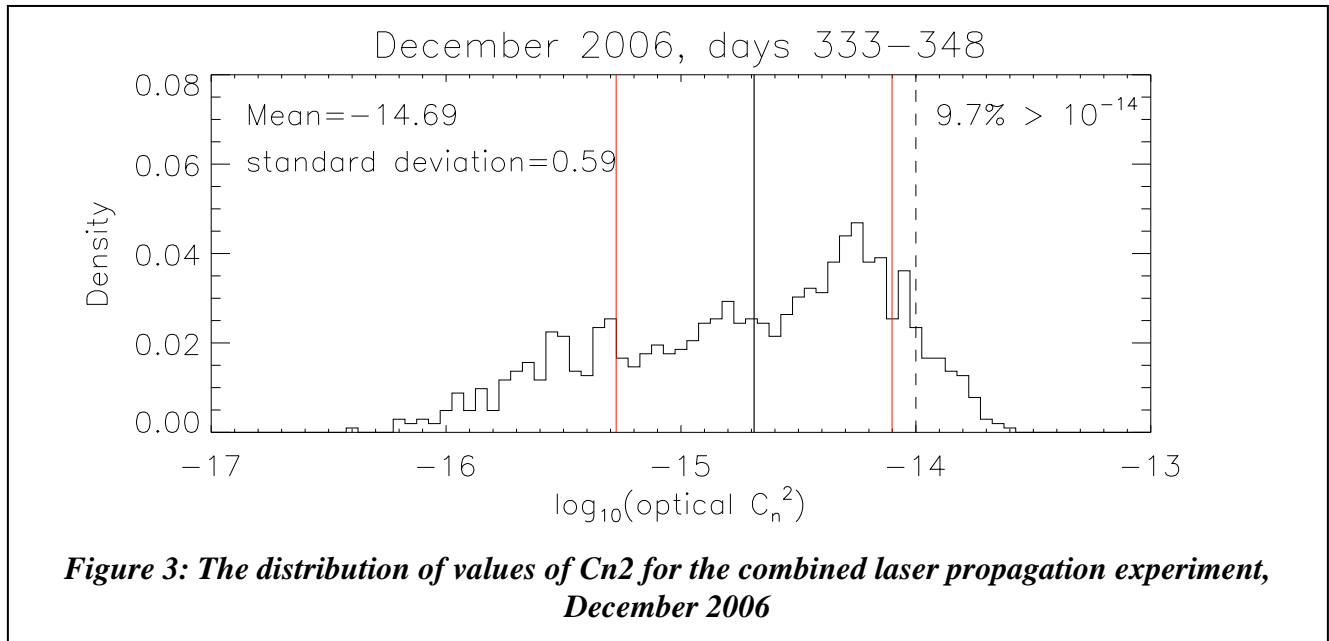
The comparison is displayed in Fig. 1. We have broken the data into two subsets, corresponding to the determination of  $C_n^2$  from the Scintec BLS2000 scintillometer. The scintillometer calculation of  $C_n^2$  is shown on the abscissa as  $C_n^2$ : BLS, and the subset is separated according to  $C_n^2 < 10^{-15}$  and  $C_n^2 \geq 10^{-15}$ .

Note that for the set for which  $C_n^2 \geq 10^{-15}$  we are not able to accurately determine a corresponding measurement using the beam wander method. This is due to the fact that at higher turbulence levels, the beam-wander and beam spread together cause significant proportions of the incoming beam to fall outside the 56cm receiver aperture.

In fig. 2,  $C_n^2$  values computed from our recorded optical signal with the dual-band scintillometer are displayed as black '+'-signs. Overlaid on this is the  $C_n^2$  predicted by the marine turbulence model, NSLOT (Navy Surface Layer Optical Turbulence), shown with green squares. Finally, a point measurement of fluid-dynamically derived  $C_n^2$  is determined from sonic anemometer measurements from a mid-path buoy.



The distribution of values of  $C_n^2$  determined from the BLS2000 scintillometer is shown in Fig. 3 . This distribution can also be used to understand the comparison in Fig.1: when  $C_n^2 > 10^{-15}$  the centroid-wander technique fails, due primarily to loss of beam intensity outside of the 56 cm aperture.



**EOSTAR upgrade:** It is important to develop a reliable background simulator for infrared image analysis. Our EOSTAR upgrade utilizes the MIBS (Maritime Infrared Background Simulator) software to generate sea and sky backgrounds. The backgrounds are based on recorded IR images of sea and sky backgrounds and their spatiotemporal statistical properties. Validation of MIBS has shown very good correlation with test images.

We undertook an inversion module for the TDA version of EOSTAR. EOSTAR Pro has now implemented our inversion algorithm using sub-refractive mirage imagery. The first version can analyze a point source input to deduce the range and height of a target. Work has begun to analyze the range-height analysis for an extended target.

In order to predict an accurate background three contributions to the sea radiance have been included: a) seawater thermal self-emission (thermal blackbody emission), b) reflected sky radiance, and c) reflected solar radiance. The contributions from all portions of the sea radiance are summed together after specular reflection from the facets within the footprint defined by the image pixel.

The sun glint has been modeled and is in the process of being added to EOSTAR. Imaging sequences (of up to 25 Hz) can be generated.

## RESULTS

**ANAM has been reconfigured to model a littoral environment.** The sustained testing and analysis of the ANAM algorithms has resulted in the release of a new version of ANAM: a surf source mode is now available in ANAM5.4. This new code does not offer a provision to turn off the surf mode, although this is effectively accomplished by setting the wave energy dissipation to 0. The ANAM5.3 code remains available for those users that do not want to use the surf mode. The only difference between ANAM5.3 and ANAM5.4 is the addition of the surf mode.

**NSLOT: Optical turbulence effects on laser beam propagation can be accurately predicted using incoherent scintillometers. The Navy Surface Layer Optical Turbulence (NSLOT) is an effective and accurate predictor of turbulent laser beam degradation.** Surface layer similarity theory-based models, and other scaling law analyses provide relatively accurate predictions. We found that a beam propagated over a 7075m maritime test-path to a 56cm aperture will lose significant energy. The laser measurements indicate that the upper 40% of the turbulent cases cause significant loss of power-in-bucket. Our analysis shows that scintillometer measurements of  $C_n^2$  can be used reliably as predictors of laser beam behavior.

## EOSTAR development

The TargetBuilder and EOSM (EO Signature Model) software packages have been used to generate thermal signatures of two targets (a sample incoming missile and a frigate), and work to validate the predicted signatures will continue.

The EOSTAR visualization module now includes the effects of both turbulent blurring and beam wander. It is now possible to produce an image or image sequence demonstrating the effects of turbulent image blur and beam wander.

## IMPACT/APPLICATIONS

The performance of optical and infrared systems for long-range near-surface maritime applications is usually limited by a stressing propagation environment and not by the system design. By providing a validated model set for environmental assessment, this work will enable an objective and more accurate trade-space for design studies for the Navy proposed High Energy Laser Weapons System.

This effort will also provide a framework for the test and possible integration of optical channels in the Navy communications architecture.

The detection of a submarine periscope is a current project utilizing the EOSTAR tool, and this work is a part of the development of a threat assessment tool for submarines at periscope depth.

## RELATED PROJECTS

This work will support the Maritime Naval Maritime Laser Demonstration Program and Future Naval Maritime Laser Weapon System Development Program, ONR 351. It also supports the Laser Weapons System (LaWS) program, directed by NAVSEA PMS 405.

This work supports the development of high-speed optical free-space ship-to-ship and ship-to-shore communications, and development of communication link assessment efforts supported by ONR 313.

## REFERENCES

Churnside, J. H. and Lataitis, R. J., “Wander of an optical beam in the turbulent atmosphere”, *Applied Optics*, **29**, 926-930 (1990).

## PUBLICATIONS

1. S. Hammel, D. Kichura, D. Tsintikidis, “*An analysis of laser beam degradation in a maritime environment*”, SPIE **7090**, 2008 [published].
2. J. Kusmierczyk-Michulec, A. van Eijk, M Moerman, L. Cohen, A de Jong, P. Fritz, “*Transmissometer versus sun photometer measurements of the aerosol optical properties*”, SPIE **7090**, 2008 [published].
3. P. Schwering, A. van Eijk, “*Application of environmental effects on sensors in land warfare*”, SPIE **7090**, 2008 [published].
4. P. Schwering, D. Bezuidenhout, W. Gunter, F. Le Roux, R. Sierberhagen, A. van Eijk, “*Infrared background analysis of bay environments*”, SPIE **7090**, 2008 [published].